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A Rotating Arm Using Shape-Memory Alloy

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Abstract

NASA's Mars Pathfinder mission, to be launched in 1996, reflects a new philosophy of exploiting new technologies to reduce mission cost and accelerate the pace of space exploration. One of the experiments on board Pathfinder will demonstrate the first use in space of a multi-cycle, electrically-activated, shape-memory alloy (SMA) actuator. SMAs are metal alloys which, when heated, undergo a crystalline phase change. This change in phase alters the alloy lattice-constant, resulting in a change of dimension. Upon cooling, the alloy returns to its original lattice formation. Wire drawn from a SMA contracts in length when heated. The reversible change in length is 3%-5%. The wire used in this actuator is a nickel-titanium alloy known as nitinol.

Introduction

Previous planetary missions have relied heavily on radioisotope thermal generators (RTG) for electrical power. Although RTGs have proven to be a reliable power source, they are expensive and politically less appealing than solar power. Mars Pathfinder, NASA's first Mars lander since the Viking-2 mission, will be solar powered. Mars offers a unique challenge to solar array designers. Since the Mars atmosphere contains large amounts of dust, the effects of dust settling onto solar panels must be considered in sizing solar arrays. Projections of power loss due to dust buildup vary from 20% to 90% over the course of a 2 year mission [1]. Unfortunately, very little data is available on the settling properties or optical opacity of Mars dust.

Among other things, Pathfinder will conduct a series of experiments to measure Mars environmental effects on solar arrays. One of these experiments [2] will measure the optical obscuration created by dust settling out of the atmosphere on to a solar cell. In what is an elegant and simple experiment, a solar cell is protected by a removable cover glass. During the course of the mission, the cover glass is occasionally moved from in front of the solar cell and the short circuit current (Isc) of the solar cell is measured. Comparing Isc with and without the cover glass in place will yield a direct measurement of the optical density of the dust that has settled on the cover glass, plus the optical density of the cover glass itself. The effect of the cover glass can be subtracted out by baseline measurements made before any appreciable dust has accumulated on the cover glass.

The design for the experiment had to meet several operational constraints: 1) a power budget of five watts for 10 seconds per day, 2) power distribution is limited to 5 volts DC up to 1 amp current, 3) short circuit protection, 4) a minimum of one square centimeter detector area, 5) a total footprint of 41.0 mm x 13.7 mm, 6) a mass not to exceed 16 grams, 7) must complete at least seven cycles on the Martian surface. The

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current working prototype uses 0.522 amp, and has a mass of 7 grams. Several actuator designs, including motors, solenoid actuators and various nitinol configurations, were tested. The present design was chosen for its simplicity and low weight.

Mechanical Configuration

The actuator consists of a rotating arm to which a cover glass is attached. The arm is approximately 3.5 cm long and must rotate 32° to completely uncover the solar cell. Figure 1 shows a top view schematic. The arm is attached to an axle which is free to rotate. A SMA wire is anchored to the axle and to a stationary point 3 cm away. The nitinol wire is heated resistively by passing a DC current through the wire. The wire heats up and contracts, pulling on the axle, which then rotates the arm and cover glass. When the current to the wire is shut off, the wire expands and is returned to the rest position by a flat spring in a "bending beam" configuration. Figure 2 shows a side view of the actuator. Figure 3 is a photograph of prototype hardware.

The axle was machined from 7075 aluminum and uses a bushing fabricated from a MoS_2-impregnated polyimide (SP-3 Vespel from Dupont). The return spring, which is also used as an electrical brush, was fabricated from 38.1 μm (0.0015 in) thick, 1095 high carbon steel. The spring was plated with copper, nickel and gold and afterward annealed at 190°C for 24 hours to prevent hydrogen embrittlement. The actuator is powered by a 150 micron diameter NiTi alloy (nitinol) wire with a 90°C transition temperature. Several different nitinol compositions, with varying transition temperatures were tested. The 90°C wire chosen was based on empirical testing of the device under the expected operating conditions. The manufacturer of the wire is Dynalloy Inc. of Irvine, California.

The mechanical leverage developed by the moment arm of the axle at the SMA attachment compared to the 3.5-cm rotating arm is about 36:1. When the arm is fully rotated, the SMA wire must supply a force of approximately 137 grams (1.34 N) to overcome the resistance of the return spring. This is well below the manufacturer's maximum recommended recovery force of 330 grams. The 3-cm-long nitinol wire contracts approximately 5%, giving about 1.5 mm of usable motion. The rotation of the axle requires a 0.6 mm contraction of the wire. By choosing the operating force conservatively and using less than the full contraction of the wire, the mechanism offers positive and robust action over a wide temperature range.

Operation and Electrical Configuration

The Mars Pathfinder consists of a lander and a small, autonomous, six-wheel rover vehicle. Once the lander is situated on Mars, it releases the rover. The rover has its own independent power system and on-board computer that controls rover functions including all experiments. It is also equipped with a transceiver for communicating with the lander. The "dust cover" experiment (also known as part of the "material adhesion experiment" or MAE) is situated on the front left corner of the rover. Figure 4 shows the rover and the position of the dust sensor.

The experiment requires that the rotating arm fully remove the cover glass from in front of the solar cell. The rover energizes the actuator, waits a predetermined time, and then measures the solar cell. No feedback signal is available from the actuator to tell the rover that the cover glass is in the fully rotated position. Although a feedback signal could easily be incorporated into the actuator, the rover computer has a very limited number of data channels available for the experiment. A qualitative feedback signal is obtained by comparing the solar cell Isc with and without the cover glass. The cover glass itself will attenuate the light by 7%. Therefore a qualitative measure of whether the cover glass has been removed is obtained by measuring at least a 7% increase in Isc when the cell is uncovered.

The mechanism actuates on a switched power supply of 5 Volts DC provided by the rover power system. The current through the SMA wire is limited using a single resistor. This is not an ideal condition. Since the SMA action is thermal in nature, the ambient temperature plays an important role in determining how much current will be required to activate the rotating arm. With a fixed power supply, the operating current must be set high enough to heat up the wire at the lowest expected operating temperature. For temperatures above the minimum, the wire will heat up more quickly and rotate the arm faster. If the wire is allowed to overheat (due to an excess of current for a relatively long time), the SMA will permanently deform and destroy the actuator. The actuator has an operating range of -50°C to 0°C. This is a large enough range that the time required to rotate the cover glass can vary from 6 to 0.5 seconds. If the rover has no feedback signal to tell it when the actuator is fully rotated, it must rely on ground-based testing of the actuator characteristics as a function of temperature to anticipate how long the actuator will take to fully rotate. In addition, the rover must have available an ambient temperature measurement at the time the actuator is used. The only other alternative available is to narrow the operating temperature range, and allow the actuator "on time" to remain constant. In summary, in order to optimize the operating range of the actuator, either the current through the wire or the "on time" of the actuator must be variable. Otherwise, a fixed current and fixed "on time", reduces the actuator's operating temperature range.

Considerations for the Mars Environment

The operating temperature of the actuator on Mars is expected to vary from -40°C to -10°C at a pressure of 8 Torr CO_2. Ground testing indicates that the main heat loss mechanism of the wire is by conduction through the mechanical and electrical connections. It was found that operation was highly dependent on the thermal conductivity of the mechanical connections of the wire. For a SMA actuator to operate at low temperatures, it is important that the wire heats up uniformly. The ends of the wire must be mechanically strong and offer good electrical contact. It is nearly impossible to have a good electrical contact without having a good thermal contact. If the ends of the wire are thermally anchored to cold mechanical connections, they will require more current to heat up to the transition temperature than does the middle of the wire. The extra current required to heat the ends of the wire will overheat the middle of the wire, causing it to fail. If possible, it is best to design the mechanism so that the mechanical connection is separate from the electrical connection, so that the

mechanical anchor for the wire can be made thermally insulating to allow the wire to heat up more uniformly. Figure 5 shows the operating current of two actuators; one with thermally insulated mechanical connections and the other with thermally conducting connections. Using insulated connections decreases the current necessary to heat up the wire and extends the operating range of the device. The flight actuator uses Mylar to reduce the thermal conductivity at the mechanical connection point. While the active portion of the wire is 3 cm long, the total wire length is approximately 4.5 cm long in order to physically separate the mechanical and electrical connections. Tests done at Mars temperature and pressure conditions have verified operation of the actuator over a temperature range of -50°C to 0°C.

Summary

A shape-memory alloy powered rotating actuator has been designed and fabricated for use on Mars. This actuator uses thermally insulated mechanical connections to achieve a more uniform heating of the SMA, reducing the operating current and extending the operating range. This will be the first multi-cycle, SMA actuator used in a space application.

References

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2. Landis, Geoffrey A. and Dennis Flood. "Solar Distribution and Dust Obscuration Sensor." Presented at the MESUR Science Definition Team Meeting, Nov. 5-6, 1992, Jet Propulsion Laboratory, Pasadena, CA.

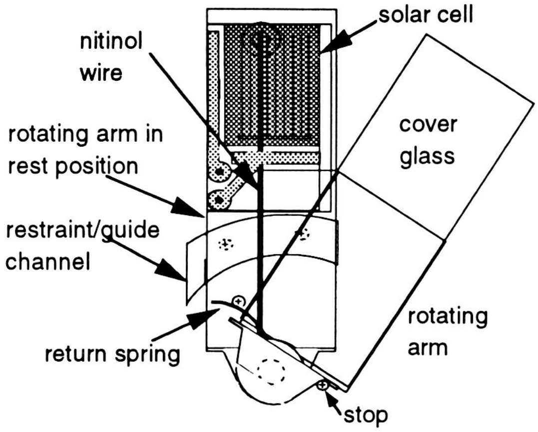

Figure 1) Top view of actuator.

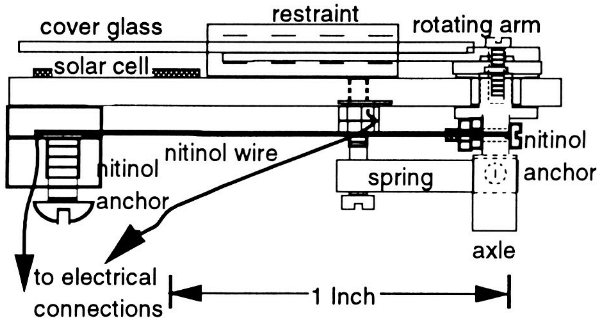

Figure 2) Side view of actuator.

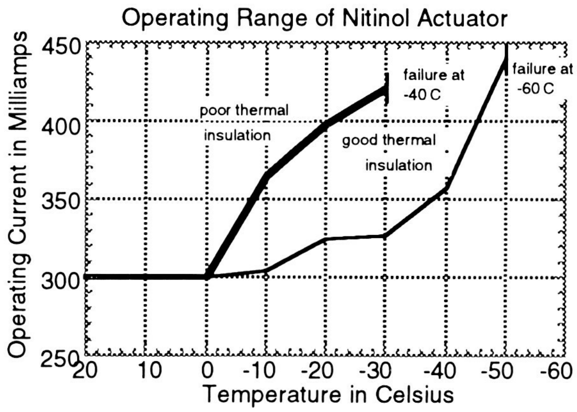

Figure 5) Insulation of mechanical connections improves operating range.

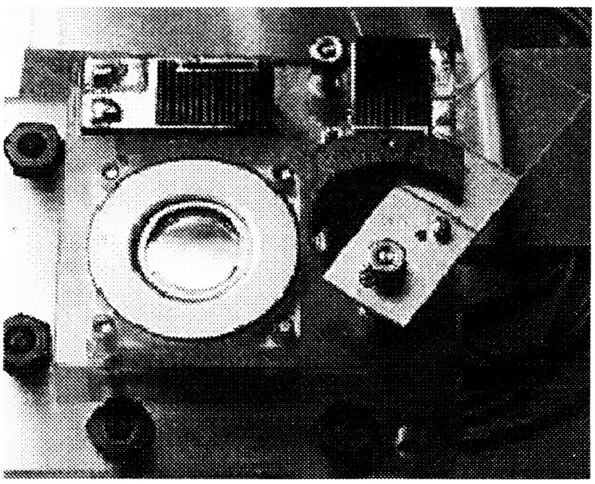

Figure 3) Photograph of the prototype material adhesion experiment. Actuator is on the right side, in the deployed position.

Figure 4) Pathfinder rover showing the location of the material adhesion experiment (MAE).